Advanced Materials Research Vols. 488-489 (2012) pp 1777-1782
Online available since 2012/Mar/15 at www.scientific.net
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doi:10.4028/www.scientific.net/AMR.488-489.1777

Application of Taguchi Optimization Method in Active Vibration Control ofa Smart Beam

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Keywords: Taguchi method, Design of experiments, Active vibration control, Smart structures, Piezoelectric patch.

Abstract. Cantilevered beams can serve as a basic model for a number of structures used in various fields of industry, such as airplane wings, turbine blades and robotic manipulator arms. In this paper, the active vibration control of a smart cantilevered beam with a piezoelectric patch is studied. Additionally, the optimization of influential parameters of piezoelectric actuator for the purpose of vibration suppression is performed. Initially, the finite element modeling of the cantilevered beam and its piezoelectric patch is described and the implementation of a control system for vibration suppression is introduced. Transient response of the system under impact loading, with and without controller, is simulated using ANSYS. Taguchi's design of experiments method is used to investigate the effect of five geometric parameters on the vibrational behavior of the system. It is shown that, optimal selection of levels for geometry of the piezoelectric actuator and sensor, can dramatically improve the dynamic response of the smart beam.

Introduction

A smart structure can be defined as a structure or structural component with bonded or embedded sensors and actuators coupled with a control system which enables the structure to respond to the external stimuli in order to suppress the undesired effects or enhance the desired effects [1].Piezoelectric materials have been used extensively as the distributed sensors and actuators in a wide range of applications, such as shape control, vibration suppression and noise attenuation [2]. Many studies have focused on the modeling of piezoelectric direct and inverse effects [3–5]. Commonly, the finite element method is used to solve the coupled electromechanical systems.

The purpose of active vibration control is to reduce the unwanted vibrations of a mechanical system by means of modifying the system's structural response [6]. In an active structure, sensors detect vibrations while actuators influence the structural response of the system. The controller must suitably manipulate the sensor's signal and modify the system's response which leads to an acceptable suppression of vibration. Application of smart structures to vibration control may be found in[7]. Literature reviews show that much research on active vibration control, hybrid control and optimal placement and sizing of the actuators have been carried out, concerning the piezoelectric smart structures, and significant achievements have been obtained [8–10].

The performance of vibration control for flexible structuresdepends on the applied voltage, location of the piezoelectric actuator or sensor and dimensions of piezoelectric actuator [11]. In the present paper the active vibration control of a smart beam under impact loading is investigated using finite element method. The optimal dimensions and location of piezoelectric actuator and sensor is obtained using Taguchi method. Results showthat using the optimal parameters settings, the unwanted vibrations of the smart beam is effectively suppressed.

Piezoelectric Smart Structure

Finite Element Model. In this study SOLID45 and SOLID5elements are used to model the beam and the piezoelectric actuator, respectively.The finite element model is shown in Fig.1. Cantilever boundary condition is applied to fix the nodes at the beam's support. The voltage degree of freedom is coupled for the nodes at the top and bottom surfaces of the actuator. The beam and the piezoelectric actuator are made of aluminum and PZT-5H [12], respectively. The dimensions and properties of beam are reported in Table 1.

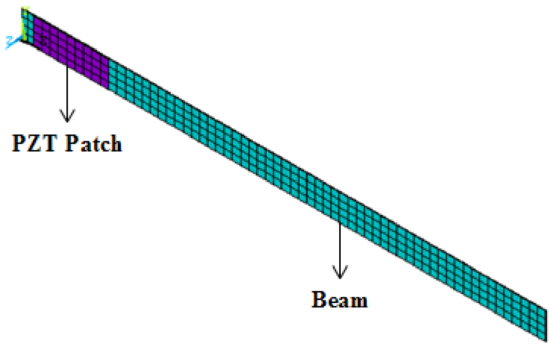

Figure 1 Finite element model of the smart beam

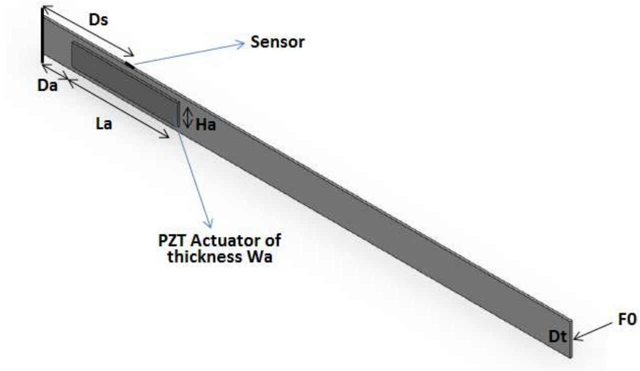

Figure 2 The configuration of smart beam

Table 1Dimensions and mechanical properties of the cantilever beam

Beam Dimensions			Mechanical Properties		
Thickness	Width	Length	Elastic Modulus	Density	Poisson's ratio
2 [mm]	30 [mm]	500 [mm]	68e9 [Pa]	2800 [kg/m^3]	0.3

The time step is commonly chosen as dt = 1/(20f_n), where f_n is the highest natural frequency to be considered. However, as changing piezoelectric actuator size affects the beam's natural frequency, for all cases a fixed time step is useddt = 0.005 sec < 1/(20f_1), where f_1 is the first vibration mode of the structure. In the transient analysis, coefficients of Rayleigh damping are defined as $\alpha = \beta = 0.001$.

Control Algorithm. In this study a Direct Strain Feedback Control (DSFC) is utilized to calculate the required active voltage to the piezoelectric patch in order to damp out the unwanted vibrations. A smart beam under impact loading is shown in Fig. 2. An impact force in the form of a step, F_0= 2 N, is applied at the beam's tip. It is then removed during the subsequent steps. At each time step, the strainε at the sensor locationis calculated from the finite element model. The reference input is zero in order to suppress the vibration. K_s, K_c and K_v are the sensor, control and power amplification factors and are chosen to be 1000, 1000 and 5.5, respectively. In this study only the proportional control is considered. Deflection at beam's tip, D_t, is observed and used in evaluating the performance of the control algorithm. The macro, which calculates the active voltage based on the applied closed control loop, is developed in ANSYS parametric design language and is given in Table 2.

Table 2 Direct Strain Feedback Control (DSFC) macro

```
*do,t,2*dt,tim,dt
!Read Sensor Displacement Data
*get,U1,node,N1,u,x
*get,U2,node,N2,u,x
err=0-Ks*(U2-U1)/SIZ
!Define Piezoelectric Voltage
Va=Kc*Kv*err
*if, Va,gt,235*Wa,then
Va =235*Wa
*elseif, Va,lt,-235*Wa,then
Va =-235*Wa
*endif
!Apply Piezoelectric Voltage
cmsel,s,TOP
d,all,volt,Va !Top Electrodes
allsel,all
time,t
solve
*enddo
```

Design of Experiments

The five parameters shown in Fig. 2,namely location (D_A), length (L_A), width (H_A) and thickness(W_A) of piezoelectric patch and sensor's position (D_S) are the most influential factors which affect the performance of the control system. To find an optimum setting for these parameters, different levels are selected for each parameter as presented in Table 3.

Table 3Selected levels for thesystem setup parameters

Parameters		Levels of each parameter				
		Level 1	Level 2	Level 3	Level 4	Level 5
Length of PZT patch	L_A	50	75	100	125	150
Width of PZT patch	H_A	10	15	20	25	30
Thickness of PZT patch	W_A	1	1.5	2	2.5	3
Actuator's distance from support	D_A	0	15	30	45	60
Sensor's distance from support	D_S	50	60	70	80	90

*all dimensions are in [mm]

The goal is to reach maximum damping ratio or minimum settling time. Based on Table 3, there are 5^5=3125 different configurations. It is not reasonable to carry out this number of experiments to find the optimum setup.Taguchi's L25 orthogonal array is used to produce only 25 experiments [13]. Taguchi method allows calculation of the optimal parameter levels with only 25 configurations.

Results and Discussion

Finite Element Results. Combinations of the L25 array are shown in Table 4. It shows ANSYS simulation results and corresponding outputs, damping ratio (ζ) and the settling time (T_S).

Table 4 Simulation results obtained by finite element program based on Taguchi's L25 orthogonal array

Test #	L_A	H_A	W_A	D_A	D_S	ζ	T_S[s]	Test #	L_A	H_A	W_A	D_A	D_S	ζ	T_S [s]
1	50	10	1	0	50	0.0171	5.67	**14**	100	25	1	30	90	0.0524	1.81
2	50	15	1.5	15	60	0.0117	7.69	**15**	100	30	1.5	45	50	0.0162	5.10
3	50	20	2	30	70	0.0046	18.80	**16**	125	10	2.5	15	90	0.0124	5.72
4	50	25	2.5	45	80	0.0042	20.41	**17**	125	15	3	30	50	0.0076	9.21
5	50	30	3	60	90	0.0032	27.03	**18**	125	20	1	45	60	0.0518	1.89
6	75	10	1.5	30	80	0.0153	5.82	**19**	125	25	1.5	60	70	0.0226	3.76
7	75	15	2	45	90	0.0076	11.07	**20**	125	30	2	0	80	0.0217	3.05
8	75	20	2.5	60	50	0.0128	6.78	**21**	150	10	3	45	70	0.0085	8.56
9	75	25	3	0	60	0.0049	15.13	**22**	150	15	1	60	80	0.0426	2.33
10	75	30	1	15	70	0.0447	2.10	**23**	150	20	1.5	0	90	0.049	1.52
11	100	10	2	60	60	0.0142	6.09	**24**	150	25	2	15	50	0.0267	2.52
12	100	15	2.5	0	70	0.0111	6.36	**25**	150	30	2.5	30	60	0.0131	5.15
13	100	20	3	15	80	0.0063	11.22								

Damping ratio is calculated by means of logarithmic decrement with the following equations,

$$\delta = (1/n) \times (\ln (x_1/x_{n+1})). \quad (1)$$

$$\zeta = 1/ [1+ ((2\pi)/\delta)^2]^{1/2}. \quad (2)$$

Where δ is the logarithmic decrement, ζ is damping ratio, $x_1$and $x_{n+1}$are the first and $(n+1)^{th}$peak amplitudes of the vibrations respectively. Settling time with two percent criterion is also calculated using the following equation,

$$T_s = 3.9/ (\zeta w_n). \quad (3)$$

Taguchi Analysis. Damping ratio (ζ) and settling time (T_s) are considered as the outputs of each testin Table 4.TheSN (Signal to Noise) ratios for all levels of each parameter are calculated and shown in Tables 5 and 6.

Table 5Taguchi Analysis: ζ versus La; Ha; Wa; Da; Ds

Response Table for Signal to Noise Ratios Larger is better					
Level	La	Ha	Wa	Da	Ds
1	-43.63	-37.63	-28.21	-36.02	-36.57
2	-37.95	-37.98	-33.97	-35.85	-37.03
3	-36.30	-36.10	-38.16	-37.74	-37.43
4	-34.48	-36.75	-40.05	-38.57	-37.71
5	-32.83	-36.73	-44.78	-37.01	-36.44
Range	10.80	1.88	16.57	2.72	1.26
Rank	2	4	1	3	5

Table 6Taguchi Analysis: T_s versus La; Ha; Wa; Da; Ds

Response Table for Signal to Noise Ratios Smaller is better					
Level	La	Ha	Wa	Da	Ds
1	-38.59	-31.94	-23.89	-29.58	-30.60
2	-32.54	-32.23	-28.43	-29.64	-31.33
3	-30.38	-30.42	-31.92	-31.86	-31.60
4	-28.20	-30.87	-33.63	-33.05	-31.87
5	-26.35	-30.60	-38.20	-31.93	-30.66
Range	12.24	1.88	14.31	3.47	1.27
Rank	2	4	1	3	5

Referring to Table 5 and 6, levels with highest SN ratiosare selected as optimum levels. These configurations optimize both damping ratio and settling time as shown in Table 7.The variables thickness and length of the piezoelectric patch have the highest range and are therefore the most influential variables.

Table 7 Taguchi's suggested optimum configuration

Optimization Criterion	L_A	H_A	W_A	D_A	D_S
Maximum Damping Ratio	150	20	1	15	90
Minimum Settling Time	150	20	1	0	50

Figures 3 and 4 present the outputs of all 25 tests from Table 4as well as the two suggested optimal cases, in terms of vibrations frequency. It is obvious that nearly 70% of L25 simulation outputs for damping ration are below 0.02. However, Taguchi has suggested a configuration with damping ratio greater than 0.075. Similarly, 60% of the L25 simulation outputs for settling time are greater than 5 seconds while Taguchi's S/N ratio analysis suggests a configuration which has a settling time of less than 1.5 seconds.Fig. 5 illustrates the response of the system for the two optimum configurations based on settling time and damping ratio. In these plots, vibrations of the system for the two optimum configurations are compared with and without the implementation of control loop.

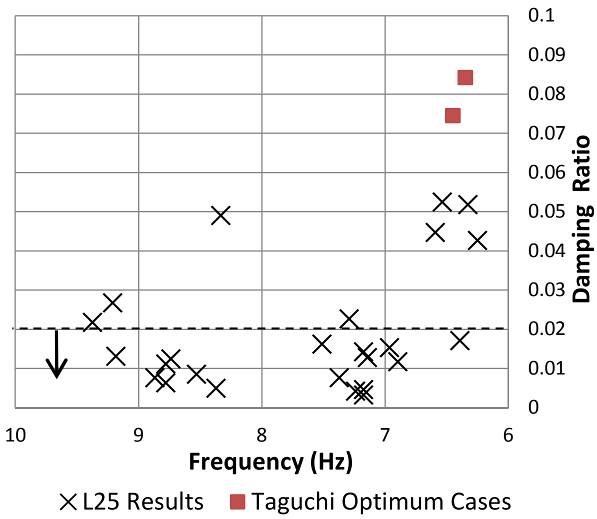

Figure 3 Comparison of Taguchi's optimal cases and L25 tests (Damping ratio vs. Frequency)

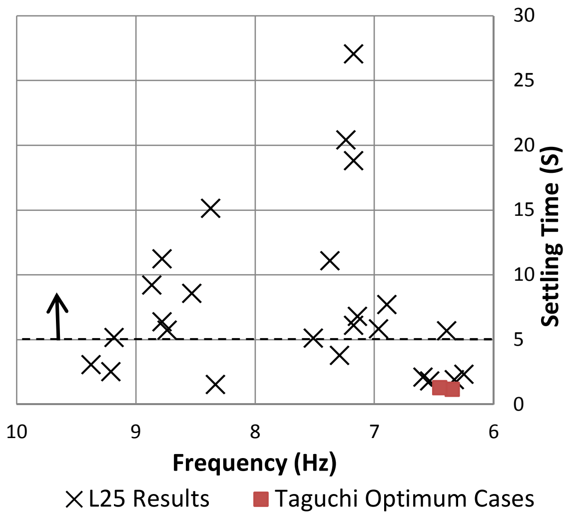

Figure 4 Comparison of Taguchi's optimal cases and L25 tests (Settling time vs. Frequency)

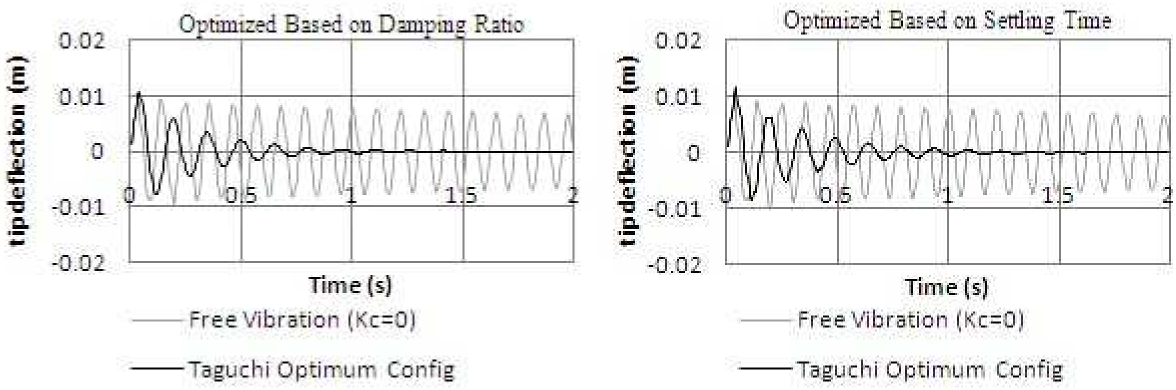

Figure 5 Comparison of system's response with and without applying the optimum control setup

Conclusion

Utilizing an efficient control methodalong with optimum selection of piezoelectric actuator and sensor dimensions, improves the functionality of smart structures in suppression of unwanted vibrations. In this paper, the optimal placement and sizing of piezoelectric actuator and sensor is obtained using Taguchi design of experiments method. According to S/N ratio plots, the thickness and length(W_A and L_A) of the piezoelectric patch have considerable influence in comparison with other parameters.It is shown that by applying the optimized active vibration control, the vibrations are dampedsignificantly faster. A combination of finite element solutions and optimization analysis based on design of experiments methods can help the designer to configure the smart structure efficiently without the need to perform extensive experiments.

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